FATIGUE ENHANCEMENT OF A

CARBON FIBER REINFORCED NANOCOMPOSITE

A Senior Scholars Thesis

by

JUSTIN W. WILKERSON

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

April 2008

Major: Aerospace Engineering

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Associate Dean for Undergraduate Research: Robert C. Webb

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ABSTRACT

Fatigue Enhancement of a Carbon Fiber Reinforced Nanocomposite (April 2008)

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The primary objective of the present investigation is to study the fatigue characteristics of a woven carbon fiber reinforced polymer which has been modified with either amine or fluorine functionalized carbon nanotubes on the fiber-matrix interface. Multi-wall functionalized carbon nanotubes are sprayed onto both sides of each fiber at 0.2-wt % with respect to the fibers. The composites are fabricated using high temperature vacuum assisted resin transfer molding with four-harness satin weave fabric and EPON 862/Epi-Kure W epoxy. Due to the heterogeneous nature of carbon fiber composites, under dynamic loading the composites undergoes a series of complex failure mechanisms: matrix cracking, fiber-matrix debonding, fiber fracture, and buckling. It is believed that debonding of the fiber-matrix interface is the most crucial of these failure mechanisms. Debonding of the fiber-matrix interface critically hinders the matrix's ability to transfer loads to the fibers, leading to a poor distribution of load. Due to this distribution, one of three failures occurs: individual yarns of fibers are overloaded and fracture, the matrix losses strength and buckles, or a mixture of the two occurs. It will be shown that

functionalized multi-wall carbon nanotubes can strengthen the fiber-matrix interface, resulting in fatigue life improvement.

The research investigates this behavior for both tension-tension and tension-compression fatiguing. It is believed that improvements will be best at negative R-ratios and high cycle regimes, because the damage is almost entirely matrix dominated occurs under these conditions. Results have shown improvements in static tensile properties of about twenty percent and an order of magnitude improvement in the fatigue life. Fractographic analysis reveals that the nanocomposites can withstand far greater matrix damage prior to final failure. In addition, both optical and scanning electron microscopy indicates that the nanocomposite exhibits reduced fiber-matrix debonding.

ACKNOWLEDGMENTS

The author would first of all like to acknowledge the guidance and support of Drs. Daniel Davis and Dimitris Lagoudas, without whom the accomplishments of this investigation would have not been achieved. Drs. Jiang Zhu and Enrique Barrera must be acknowledged for their collaborative research efforts. The author gives special thanks to Patrick Klein for providing training in the fabrication and quality assurance techniques. The hands-on training in fabrication and microscopy techniques by Ryan Sager is much appreciated. The author graciously appreciates the MTS test frame training provided by Daniel Ayewah. Thank you all for your extensive and continued support.

NOMENCLATURE

ASTM	American Society for Testing and Materials
CNT	carbon nanotubes
F	functionalized
H-VARTM	high temperature vacuum assisted resin transfer molding
MWNT	multi-wall carbon nanotubes

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CHAPTER I

INTRODUCTION

A composite is a marriage of multiple constituents, which work together as a material system to achieve desired superior mechanical, electrical, or thermal performance. Usually, composites are composed of a continuous compliant phase called the matrix, and a discontinuous stiff phase called reinforcement. A bond between the reinforcement and matrix phases is required to define the composite as a material, rather then a structure. The location of this bond is known as the fiber-matrix interface, but is sometimes thought of as an independent phase called the interphase. The mechanical properties of a composite material are highly dependent on the strength of the fiber-matrix interface, geometry and distribution of the reinforcement, and, of course, the properties of the individual constituents.

Depending on the application of the composite, the phases take on different roles which serve to classify the composite. Low performance composites are often composed of short fibers or particles that stiffen and locally strengthen the material, but the load is handled by the matrix. In contrast, high performance composites are characterized by continuous load bearing fibers. The matrix takes on a crucial supporting role; protecting the all important fibers, transferring local stress between fibers, and providing body to the material. The strength of the fiber-matrix interface is important, because it determines how well the fiber and matrix work in this systematic manner.

This thesis follows the style of The International Journal of Fatigue.

The concept of fibrous reinforced material is far from novel. The biblical book of Exodus refers to the oppressed Israelites being forced to make clay bricks without straw-reinforcement. The origins of modern composites are rooted in the, somewhat accidental, discovery of fiberglass during the lettering process of glass milk bottles in 1930. Wright Patterson Air Force Base developed two planes with composite wings, which were successfully flown in 1942. This marked the first major usage of composites as structural components for aerospace applications. Unfortunately, this was the last airplane of its kind manufactured for many years. Recently, there has been a resurgence of aircraft built of a considerable percentage of composite material; for example, the Boeing 787, the Lockheed Martin F-35 Lightening II, and the B-2 Bomber. Much of the recent interest has been fueled by the exceptional specific quasi-static and fatigue strengths, arguably, the most important design considerations for aerospace vehicles.

A girth of fatigue knowledge exists for metals, as a result of numerous investigations conducted over the last 150 years. However, for composites this level of comprehension does not yet exist. In fact, in the 1970s, it was a common belief that carbon fiber composites did not experience fatiguing. We now know this to be false; composites experience a complex series of failure mechanisms under cyclic loading conditions.

For metals, fatigue is a phenomenon that results from the movement of dislocations. The damage typically is localized about surface defects, and the final failure of a metal is a 45° shear failure. Since composites are material systems composed of constituents with

highly differing properties, the failure mechanisms are rather complex. For uniaxial and biaxial continuous fiber composites subjected to uniaxial cyclic loading, micro cracking normal to the loading direction forms within the matrix. The composite experiences this micro cracking throughout the cyclic loading. Next, cracks propagate along the fiber-matrix interface. This leads way to the question of what begins this damage process. It is likely due to a critical micro cracking density, micro cracking propagating to the fiber-matrix interface, and fiber-matrix interface voids that result from fabrication. This damage is the root cause of delamination, significant debonding of the fiber and matrix, which is acknowledged as the critical failure mechanism. At some point, due to continued degradation of the matrix (micro cracking) and debonding of the fiber-matrix interface, the matrix begins having difficulty performing its primary role, distributing the stresses among the fibers. This leads to fiber yarns being over loaded and fracturing. Under particular compressive loading conditions, this final failure mechanism may not fully occur due to a buckling failure. In addition, the delamination failure mechanism is exaggerated due to Poisson's effect.

In attempting to further improve the mechanical capabilities of composites, there are two viable approaches: improving the mechanical properties of the individual constituents and improving the ability of composite to act as a material system. However, taking the first route yields limited success, because it does not address the primary mechanical deficiency, the fiber-matrix debonding. The thinking then became that providing reinforcement in the z-direction to the composite would alleviate some of the stress placed upon the fiber-matrix interface. Investigations of 3-diminsional composites and

composites with z-directional stitching were conducted. Both had significant inherent deficiencies. A 3-diminsional composite is simply not as strong in tension compared to a uniaxial or woven composite. Stitching was thought to be a solution which would not decrease the in plane properties of the composite, since it did not require orienting the fibers differently. Unfortunately, it was found that this solution yielded limited success. The stitching process damaged the fragile fibers. The studies showed improvements under particular compressive loading conditions, but degradation under other conditions.

It now appears that the best solution lies within strengthening the fiber-matrix interface itself. Obviously, this includes researching epoxy systems which may better adhere to the fibers. However, it is believed that the truly revolutionary improvements will be a result of the proper utilization of a truly phenomenal material, the carbon nanotube, or CNT.

Successful fabrication of CNT nanocomposites requires overcoming the poor interfacial adhesion and dispersion intrinsic to untreated CNT. These challenges are best overcome with amine functionalized carbon nanotubes, or F-CNT, because amine molecules exhibit high reactivity. Zhu et al. covalently grafted organic molecules to single-wall carbon nanotubes, or SWNT, and dispersed the F-CNT in epoxy. The modulus and strength increased by 68% and 22.9%, respectively, with 4 wt% of CNT [1-2]. Yang et al [3], Blake et al [4], and Hwang et al. [5] have all shown improvements in mechanical properties through F-CNT reinforcement.

Qian et al. initiated crack propagation under TEM and showed CNT bridging [6]. Marrs et al. improved the fatigue strength of a copolymer by 592% with the addition of 5 wt % of MWNT. The study showed MWNT reorienting normal to the crack face, while bridging the crack tip [7]. Exhibiting this same behavior on the fiber-matrix interface would result in phenomenal improvements in fatigue life. The bridging of F-CNT would hinder, and possibly alter, the debonding of the fiber-matrix interface failure mechanism. This study will take nanocomposites a step further by using CNT to not only improve the overall characteristics, but, more importantly, to reinforce a critical weakness of the material on the nanoscale.

CHAPTER II

METHODOLOGY

Composite fabrication

Two types of composites are fabricated: neat and F-MWNT composites. The only intended difference in these types of composites is what type, if any, of F-MWNT are sprayed onto the IM7 four harness satin weave carbon fiber fabric. Twelve squares of carbon fiber fabric are cut from a roll of carbon fabric to be used in the carbon fiber fabric. In order to fabricate neat composites the spraying procedure is skipped. For F-MWNT composites, the carbon fiber fabric squares are taken to Rice University to be sprayed with F-MWNT. The carbon fiber fabric is then brought back to Texas A&M. From this point on the fabrication process for each type of composite is intended to be the same. The following lays out the procedure used for fabricating each type of composite. From here on out whether the carbon fiber fabric holds F-MWNT or not it will be referred to as carbon fiber fabric since the fabrication process is intended to be the same.

Twelve 8" x 8" plies of woven IM7 carbon fiber fabric are cut from a roll of carbon fiber fabric. Cutting carbon fiber fabric requires a skilled person as the fabric is extremely fragile in this state. The properties of the fabricated composite may differ if the fabric weave of ply is altered; in this case, a ply with altered fabric weave should not be used. The weave of the roll of carbon fiber fabric is mostly held in place by fiber glass strings in the middle of the roll and stitching on the edges. However, these strings should be carefully removed with tweezers and the stitching on the edges should be cut off to insure

a balanced and symmetric composite, in accordance with ASTM standards. One must be careful to assure that the orientation of these plies is maintained, because it will later be necessary to stack the fibers in a way such that the fabricated composite will be balanced and symmetric. The mass of the fibers must be determined using a balance accurate to within a tenth of a gram, the mass will later need to be known to calculate the fiber volume fraction.

Next, three sheets of vacuum bag material are cut with the following dimensions: 9.75" by 12.75"; 13" by 17"; and 18" by 20". High precision is not necessary for the two bigger sheets of vacuum bag material as the excess of the edges will later be trimmed off. Peel ply material is a white silky cloth which will be the only material used in direct contact with the carbon fiber fabric, since this material does not permanently adhere to the carbon fiber fabric during the curing process. An 8.25" by 10.75" sheet and an 8.25" by 11.25" sheet of peel ply material are cut. In order to insure consistent resin flow over, under, and through the carbon fiber fabric, screen material is used. Four sheets of screen material are cut with the following dimensions: 8" by 10.5"; 8" by 10.5" cut at 45°; 8" by 11.5"; and 10" by 13.5". Breather material is a white cotton material used to prevent air from being trapped between the two vacuum bags. Four strips of breather material are cut with the following dimensions: 2" by 13.5"; 2.25" by 12.5"; 2.25" by 13"; and 4.25" by 15". These sheets of vacuum bag, peel ply, screen, and breather lay up materials will be used in the lay up procedure of the H-VARTM process.

The lay up procedure consists of laying up the plies of carbon fiber fabric and sheets of lay up material in the correct orientation, in accordance with the H-VARTM procedure. First double sided vacuum sealant tape is laid down on the edges of a 16” by 18” glass plate; this will size the outer vacuum bag. Position the glass plate such that the 18” edges of the glass plate are on the right and left hand side of the plate, and the 16” edges of the glass plate are on the top and bottom of the plate. More double sided vacuum sealant tape is used to form a 10” by 13.5” rectangle 1.5” offset from the right edge of the glass plate. This rectangle should be centered between the top and bottom edges of the glass plate. Liquid mold release agent is lightly applied with a lent free paper towel to the glass surface on the inside of the inner smaller rectangle; the liquid mold release agent requires five minutes to dry. The smallest sheet of vacuum bag material is centered within the inner rectangle, and the corners of this sheet are taped down to the glass surface with small pieces of scotch tape. The 11.5” sheet of screen material is laid down is off set from the bottom of the sheet of vacuum bag material by 0.25”, and the 11.25” sheet of peel ply material is centered on this sheet of screen material. The corners of both the sheet of screen material and sheet of peel ply material are taped down to the sheet of vacuum bag material. Now, the plies of carbon fiber fabric can be laid down on the peel ply material. The carbon fiber fabric should be laid down such that it is offset 0.25” from the bottom of the peel ply material; however, the carbon fiber fabric must be oriented correctly as it is laid down.

The plies of carbon fiber fabric are oriented in a 0°/90° fashion; this orientation is said to be symmetric and balanced. Figure 2 shows this particular lay up. The first square ply of

carbon fiber fabric is laid down on the peel ply keeping the orientation of the roll. The next ply is rotated 90° about its center, and stacked on top of the first ply. The third ply is not rotated, the fourth is, the fifth is not, and the sixth is. This is the first stack of six carbon fiber fabric plies; another stack of six carbon fiber fabric plies is produced identical to the first stack, and placed next to the first stack in the same orientation. The second stack is then flipped over onto the first stack about the gap between the two stacks.

The remaining sheet of peel ply material is placed on the top of carbon fiber fabric stack, insuring that the bottom edges of the peel ply material and carbon fiber fabric stack are aligned. The two smaller sheets of screen material are placed on top of the peel ply material, with the 45 degree screen on the very most top. The corners are again taped down with small pieces of scotch tape. The lay up is now ready for the bagging process. Figure 1 is a schematic of what the lay up will look like prior to being ready for the bagging process.

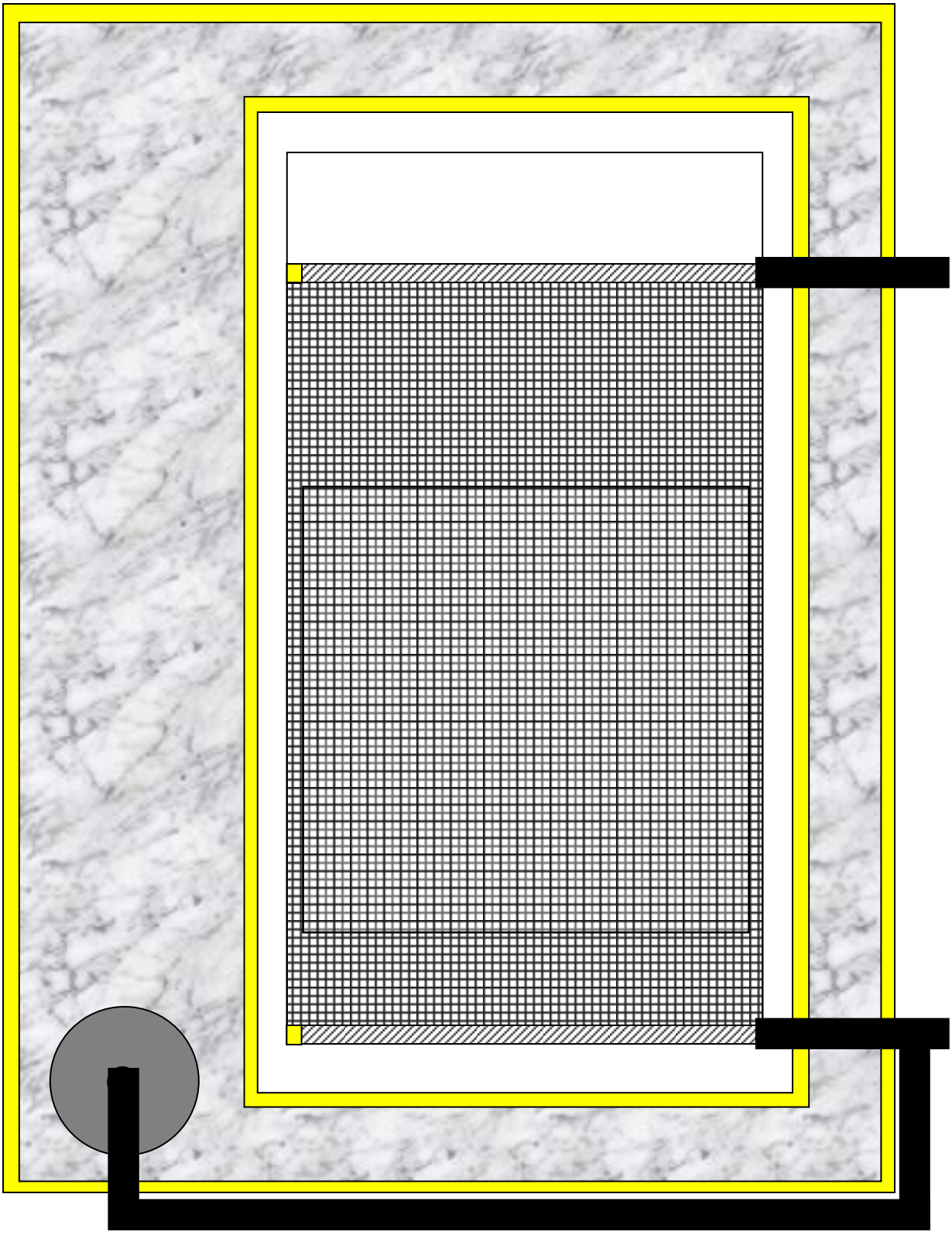

Figure 1. Schematic of H-VARTM process

Now a method of delivering the resin to the carbon fiber fabric, once the bag is seal shut. This is accomplished through three inlets to the vacuum bag. All three inlets cross the boundary made by the outer vacuum bag, and two of the inlets also cross the boundary of the inner vacuum bag. One of the inlets that cross into the inner vacuum bag will deliver resin to carbon fabric. The other two inlets remove air from the outer and inner vacuum bags in order to apply vacuum pressure to the stack of carbon fiber fabric.

A 9.75” piece of stretched out spiral tube is inserted 1.25” into a 6” piece of Viton tubing. The other end of the spiral tube is closed with a small piece of vacuum sealant tape. This assembly is placed on the top edge of the top most peel ply material, with the black Viton tubing laying over the right edge of the glass plate. The portion of Vition tube which is lying over the sealant tape attached to the glass plate is wrapped with a strip of vacuum sealant tape; the Viton tube wrapped with a strip of sealant tape is then attached to the sealant tape attached to the glass. Sealant tape is then rolled into a small cylinder of diameter equal to that of the Viton tube. Two of these tape rolls are placed on the two strips of sealant tape on the left side of the glass plate. Any overlap of tape is matched on both sides for symmetry. An identical inlet set up is assembled on the bottom edge of the bottom most vacuum bag material. The medium sized sheet of vacuum bag material is laid over the inner rectangle of sealant tape to form the inner vacuum bag.

At this point the quality of the inner bag must be checked, this is accomplished through a vacuum check. This consists of shutting the top inlet with a clamp, and applying vacuum pressure to the bottom inlet with a vacuum pump. The vacuum pressure is held

constant for one hour, and then the vacuum pump is turned off after sealing both inlets. The vacuum pressure is then measure after one hour, if there is less then a five percent decrease in vacuum pressure then the vacuum bag is acceptable.

The outer bag is then assembled. First the largest sheet of screen material is laid over the inner bag, followed by the four strips of breather material filling the gaps between the inner and outer bags. A metal vacuum inlet is placed at the bottom left corner on top of the breather material. The largest sheet of vacuum bag material is placed over the entire assembly and sealed shut. This inlet is connected to the bottom right inlet and the vacuum pump with a long piece of Viton tubing. Vacuum pressure is pulled applied to both the inner and outer bags for six hours.

At this point the assembly is ready for the infusion process. The assembly is placed on top of heating pads, and the assembly is heated such that the bottom of the glass plate reaches a temperature of 140°F and the top of the outer bag reaches a temperature of 115°F. The vacuum inlet at the bottom right of the inner bag is unclipped, because the carbon fiber fabric will give off gas when heated. This excess gas would decrease the vacuum pressure if it were allowed to accumulate in the inner bag. 140 grams of EPON 860 resin preheated in an oven at 122°C for 10 minutes, this will produce a better composite. The resin is then mixed with 36.96 grams of Epi-Kure curing agent W. This mixture, which will just be referred to as resin from here on out, is placed in a oven subjected to vacuum pressure at a temperature of 50°C to allow the resin to degas. Degassing is a process in which some of the micro bubbles inherent to the resin that

develop through agitation are allowed to escape by the decreased pressure. This is an important process, because micro bubbles increase the void content of the composite, thus decrease its mechanical properties. The inlet at the bottom right of the assembly is clamped off. A plastic container, wrapped in a heating pad set to a temperature of 50°C, holds the degassed resin and is attached to the top right inlet with a clear piece of tubing. The clamp impeding the resin flow is loosened to allow resin to flow through the carbon fiber fabric at a rate of a quarter inch per minute. Once the peel ply is completely saturated with resin the top right inlet is clamped off, and the carbon fiber fabric and resin is ready for the curing process. The assembly is placed in a preheated oven at a temperature of 122°C for 2 hours followed by a post curing at a temperature of 177°C. The pressure of the outer bag is held constant at 30" Hg for the duration of curing, and is maintained for 12 hours after curing. At this point, the composite is ready for the quality assurance tests.

Quality assurance

The most significant variables for a given type of composite, fabricated from the H-VARTM process, are the fiber content and void content. Both of these variables have been shown to significantly alter the mechanical properties of a composite, particularly under dynamic loading. By assuring that the fiber and void content adhere to a standard of acceptable variation it is possible to fabricate composites which have no significant variations in properties. This methodology is absolutely necessary to assure valid comparisons between the results obtained for the neat composite and those of the F-

MWNT. The fiber content was determined from the ASTM D3171-99, however a methodology for determining the void content needed to be developed.

Ultrasonic C-scans were performed on the composite panels to access the fabrication quality. Ultrasonic C-scans are just one of many forms of nondestructive evaluation. The composite is submerged in a bath of water; it is suspended one inch above the bottom of the water tank. A transducer sweeps over the entire composite emitting sound waves directed towards the composite. The sound waves propagate trough the water medium above the composite, through the thickness of the composite, through the water medium below the composite. The sound then bounces of the bottom of the water tank, and returns to the transducer through the water medium below the composite, through the thickness of the composite, and through the water medium above the composite. The transducer measures the percentage of sound energy that has been dissipated throughout the propagation of the sound wave. For a finite number of points in space, corresponding to locations on the face of the composite, the percentage of reflected sound energy is measured and recorded by the transducer and software, respectively. Every percentage of reflected sound energy is assigned to a color in accordance with a color palette. These recorded measurements are displayed through a C-scan, a colorful two dimensional image, which represents the results of the C-scan.

Study has shown that the amount of sound energy that is dissipated as the material propagates through an air medium at standard pressure and temperature is larger than that of the water medium and the composite medium. Therefore, assuming that voids are

composed of small pockets of air trapped within the composite the relative void content of one composite compared to another can be accessed. This methodology is not ideal, because small bubbles and pockets of trapped air accumulate on the surface of the composite as it is submerged in the bath of water. In order to minimize this inherent flaw in the methodology, the small bubbles and pockets of trapped air are swept off the surface of the submerged composite with rubber gloves. Additionally, as each composite is not an identical match in thickness or fiber content, it cannot be assured that the sound energy that would dissipate at a result of the sound wave propagating through a composite would be the same for another composite of identical void content. This is one reason for putting such effort into fabricating composites of equal fiber content and thickness.

Preliminary NDE study, showed the expected correlation between C-scan results and the number and size of voids. Two composites were fabricated, and one was purposely fabricated with a higher void content by increasing the infusion rate during the H-VARTM process. The two composites were seen to have similar fiber content and thickness. The C-scan of the voided composite showed an increase in the amount of sound energy dissipated compared to the composite fabricated using the standard H-VARTM process. In addition, the voided composite was seen to have large voids visible with optical microscopy, where as the panel produced by the standard process was seen to have none.

These two panels were tested under both static tensile loading and fatigue loading at an R-ratio of 0.1 and a cyclic frequency of five hertz. The tensile testing showed no

degradation in the ultimate tensile strength and elastic modulus properties of the voided composite compared to the standard composite. However, the fatigue testing revealed degradation of the fatigue life of the voided composite as expected.

Since void content was a variable in each composite a methodology was developed to constrain this variation as much as reasonably possible. Therefore the results were used to define a relative void content standard for the fabrication of composites used in the present investigation. The methodology consisted of defining a standard composite from which a C-scan was obtained. This standard C-scan would then be compared to the C-scans of all composites fabricated for use in the investigation. If the C-scan was found to have acceptable variation from the standard C-scan then it would be used for fatigue testing, if it did not then it was unacceptable for use in the fatigue study in this investigation. Although, according to the results, the composite could be used for static tensile testing even if the C-scan had unacceptable variation from the standard C-scan, these composites were simply not used at all to be safe. The acceptable variation from the standard was determined by finding a relationship between the increased dissipation of sound energy and decreased maximum stress for a given number of cycles to failure for a given R-ratio, compared to that of the standard composite. The acceptable comparative decrease in maximum stress was constrained to be less than statistical variation of similar tests. The quality assurance methodologies used require the fiber content and void content of all composites to be very similar, such that the only significant variable is whether or not the composite contains F-MWNT.

CHAPTER III

RESULTS

Quasi-static tensile

Tensile test were conducted for both the neat composite and the nanocomposite to determine the ultimate tensile strength and the modulus of elasticity. Testing was conducted in accordance with the ASTM standards for tensile testing of composites. Both the neat composite and nanocomposite were tested three times. The averages of these tests are shown in Fig. 2. From these results it can be seen that the ultimate tensile strength was increased by twenty percent through the introduction of F-MWNT to the fiber-matrix interphase. The modulus of elasticity was determined by placing a strain gauge on the composite during testing, and dividing the corresponding stress by this measured strain. The averages of these properties are shown in Fig. 3. It can bee seen that the modulus of elasticity was increased by approximately ten percent. As discussed in the introduction, composites are a material system. The results support the claim that these F-CNT introduced to the fiber-matrix interphase help the matrix to transfer loads to the fibers more effectively.

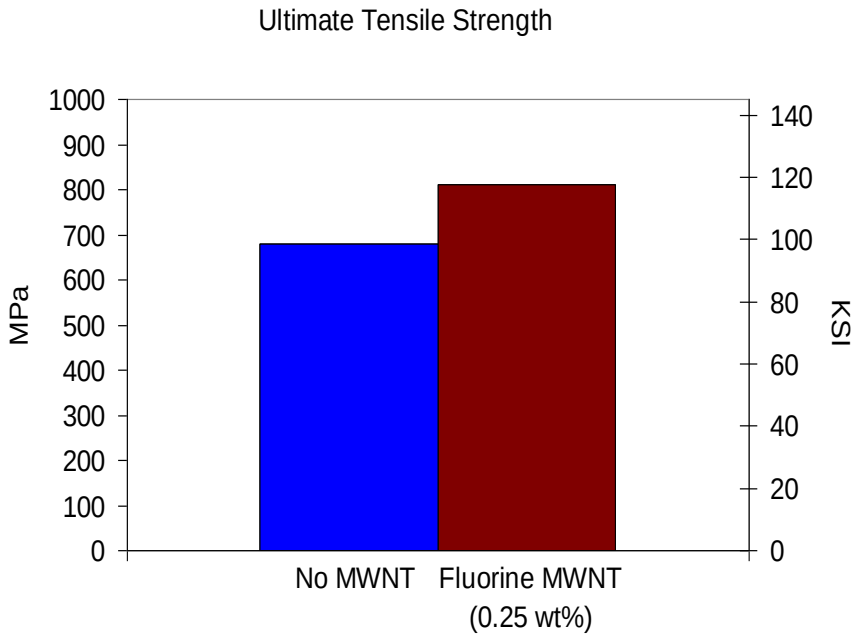

Fig. 2. Ultimate tensile strength of neat composite and nanocomposite

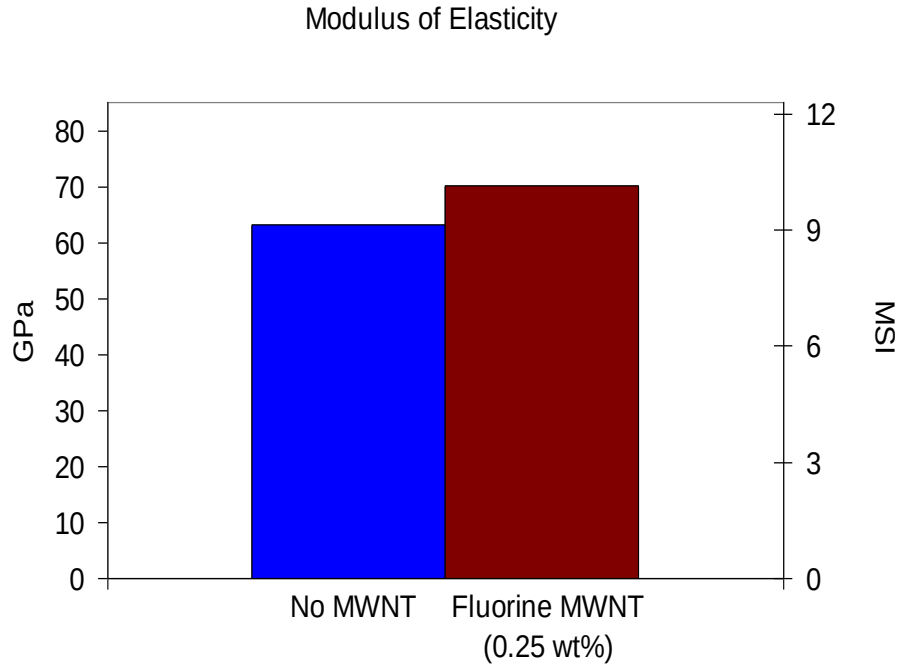

Fig. 3. Modulus of elasticity of neat composite and nanocomposite

Tension-tension fatigue

Tension-tension fatigue tests were conducted to determine the effect of using an F-MWNT reinforced fiber-matrix interface of a composite subject to cyclic loading. The tests were conducted in accordance with ASTM standards. The specimen is subjected to a minimum stress and then loaded up to a maximum stress, then is unloaded to the back to the minimum stress. This completes one fatigue cycle, and the number of these cycles completed in one second defines the cyclic frequency. Three tests were performed for each case at an R-ratio of 0.1 and a cyclic frequency of five hertz. The results of these tests are displayed in Fig. 4, an S-N plot of the result. It is shown that there is about an order of magnitude improvement in the fatigue life of the composite. This is attributed to an improvement in the fiber-matrix adhesion as an effect of the F-MWNT.

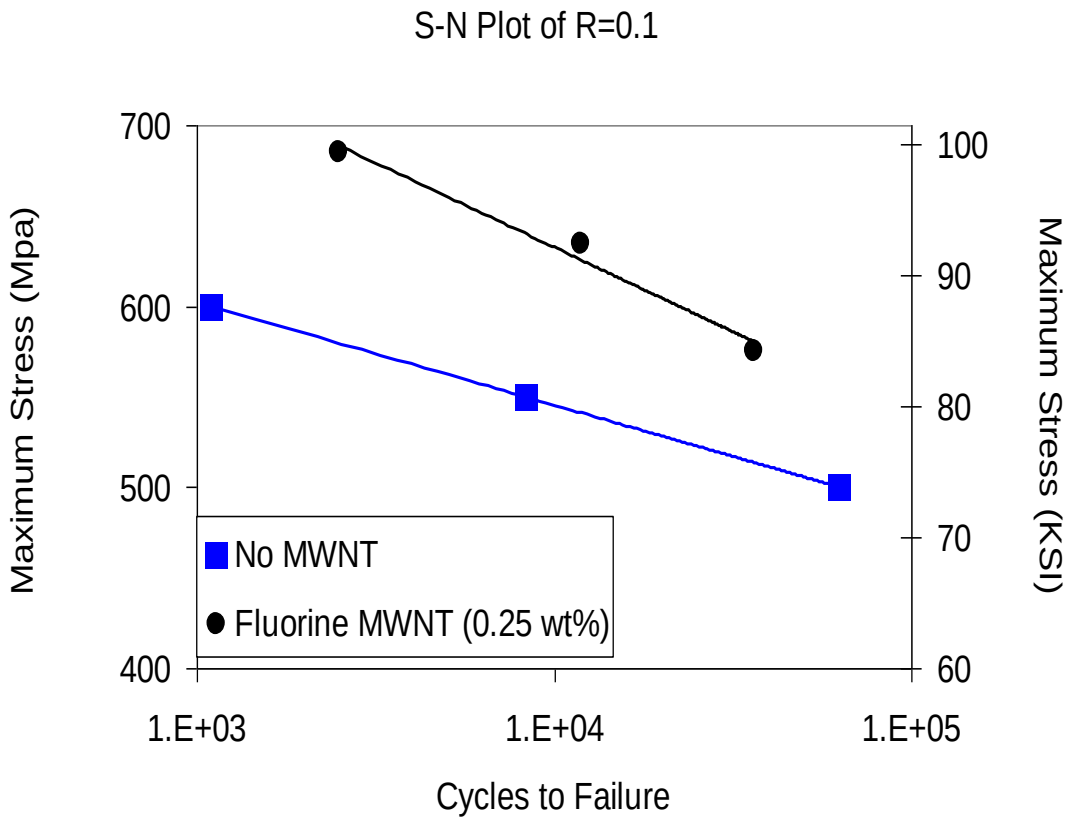

Fig. 4. R=0.1 S-N plot of neat composite and nanocomposite

Tension-compression fatigue

Tension-compression fatigue tests were conducted to determine the effect of using a F-MWNT reinforced fiber-matrix interface of a composite subject to tension-compression cyclic loading. The tests were conducted in accordance with ASTM standards. Three tests were performed for each case at an R-ratio of -0.1 and a cyclic frequency of five hertz. The results of these tests are displayed in Fig. 5, an S-N plot of the result. It is shown that there is about a two hundred percent improvement in the fatigue life of the composite. This is attributed to an improvement in the fiber-matrix adhesion as an effect

of the F-MWNT. Although this is an improvement in the fatigue life, it is not as much as what was seen in the tension-tension fatigue tests. This seems to be peculiar, as it is expected to occur vice-versa, due to Poisson's effect. As the composite is compressed its thickness is increased. This will increase the tendency of the fiber to debond from the matrix. The fact that the tension-compression fatigue life did not improve as much as the tension-tension fatigue life can be attributed to fact that the ultimate tensile strength of the composite was improved. This would benefit the tension-tension fatiguing more then the tension-compression fatiguing, since they fail due to fiber fracture and buckling, respectively.

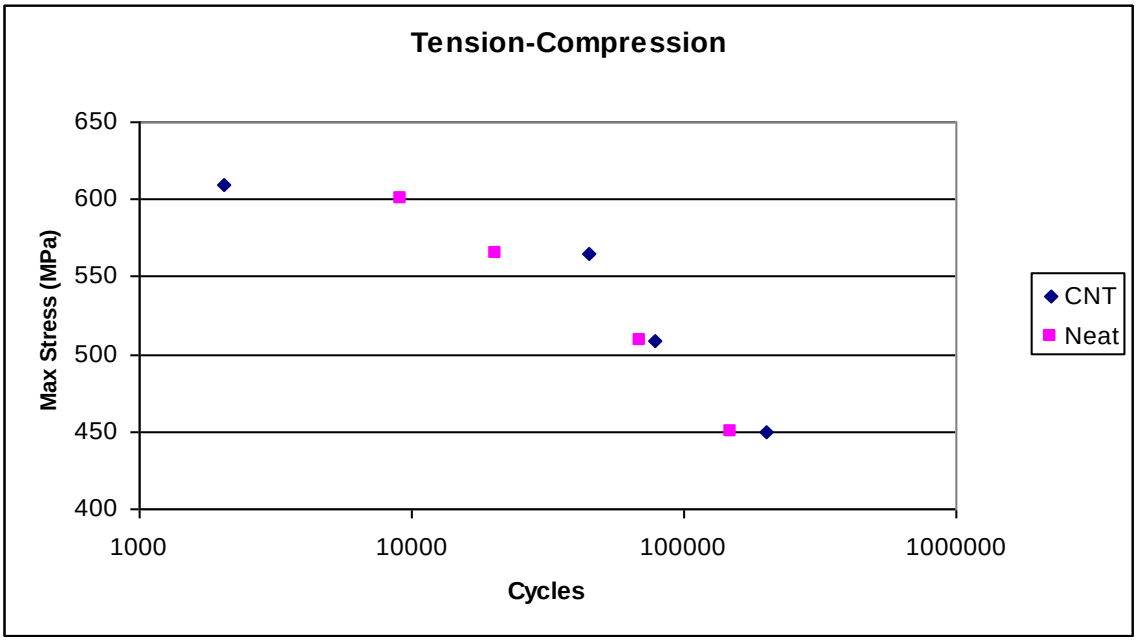

Fig. 5. R=-0.1 S-N plot of both the neat composite and nanocomposite

CHAPTER IV

CONCLUSIONS

The research investigated the benefits of introducing functionalized carbon nanotubes to the fiber-matrix interphase of a woven carbon fiber composite. The composites were fabricated using the high temperature vacuum assisted resin transfer molding process. The quality of the composites was assured by measuring the fiber content and accessing the void content through C-scans. The selectiveness of the composites used in the study insured that there would be relatively low scatter in the results of testing, as each composite used was nearly identical.

A twenty percent increase in ultimate tensile strength and a ten percent increase in modulus of elasticity, as a result of the nanotubes helping the matrix transfer loads to the reinforcing fibers. A one thousand percent increase in tension-tension fatigue life (R=0.1) and a two hundred percent increase in tension-compression fatigue life. These improvements were the result of a different strengthening mechanism. The nanotubes improved the adhesion between the fiber and matrix of the composite, thus hindering crack propagation.

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